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COMPARISON OF A THEORETICAL AND EXPERIMENTAL STUDY OF THE GAS SYSTEM IN THE M16A1 RIFLE

by

W. M. Werner

August 1971

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U.S. ARMY ABERDEEN RESEARCH AND DEVELOPMENT CENTER
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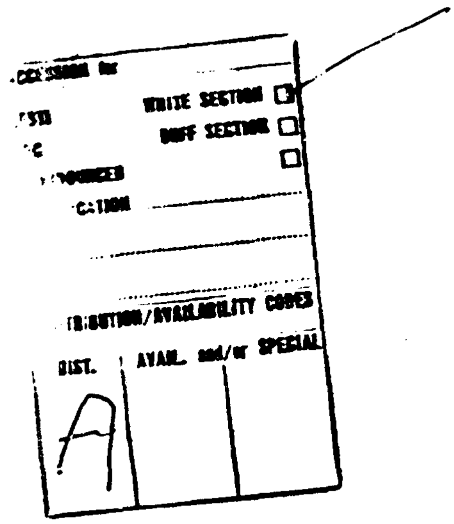

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This report also contains the results of firing experiments on the M16A1 Rifle. Theoretical predictions of the effects of changes in parameters are compared with the experimental results.

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I. INTRODUCTION

As part of a study on the M16 Rifle and ammunition, equations were derived by Dr. J. Spurk [1*] describing the quasi steady state flow of gas from a gun tube into an expansion chamber where a piston is forced into motion. Experiments were conducted with an M16A1 Rifle to determine the validity of the equations. These equations will provide the relationship between the kinematics of the mechanism and the gas pressure history in the chamber. They will be used for programming a mathematical simulation of the functioning of the mechanism on the analog computer. The simulation is needed for studying the compatibility of the rifle with the ammunition and determining the sensitivity of the system to existing variations in rifle and ammunition parameters. It will also aid in evaluating the effects of proposed changes in parameters.

The gas dynamic equations were programmed for digital computation. The input consists of pressure history in the gun tube at the gas port, physical properties of the gas, and physical dimensions of the gas system. The output includes pressure in the bolt carrier cavity and velocity of the bolt carrier as functions of time.

A rifle was modified and instrumented to measure pressure versus time at the mouth of the cartridge case, at the port position, and in the bolt carrier cavity along with displacement versus time of the bolt carrier and receiver. The time of shot ejection was recorded on all records to establish a common time reference. Weapon parameters were varied individually in the experiments for comparison with the calculations.

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* References are listed on page 41.

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II. EQUATIONS

Dr. Spurk's equations are derived using the laws of conservation of momentum, energy, and mass. The time dependent equations relate pressure, density, and temperature of the gas in the bolt carrier cavity to pressure at the gas port. Other time dependent variables in the equations are the velocity of gas flow and the velocity and displacement of the bolt carrier.

A schematic drawing of the gas system is presented in Figure 1.

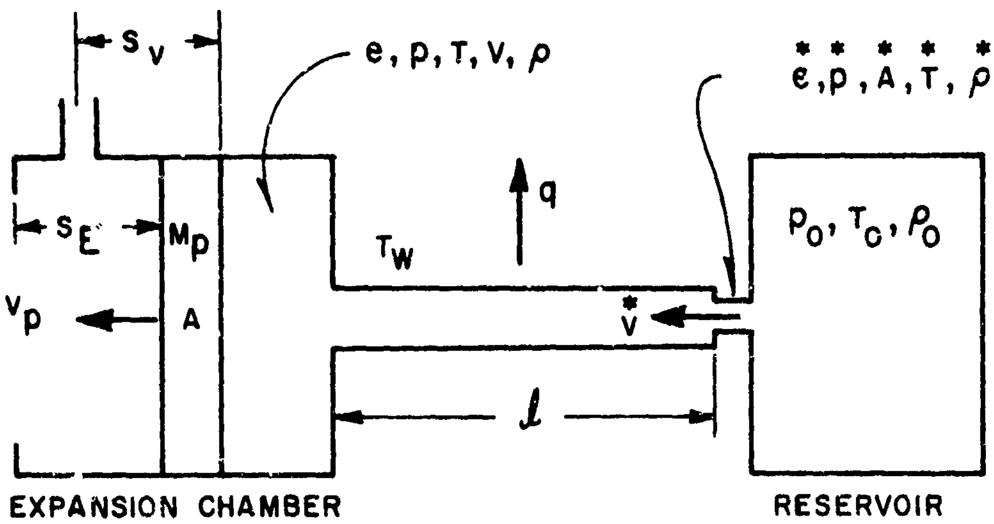

Figure 1– Diagram of Gas System

The expansion chamber or bolt carrier cavity will be referred to as the "cavity" and the gas port will be referred to as the "port."

Symbols used in the equations are defined as follows:

e heat content of unit mass of propellant gas in the bolt carrier cavity (expansion chamber)

$\overset{*}{e}$ heat content of unit mass of propellant gas at the gas port

k thermal conductivity of propellant gas

ℓ length of gas tube (port to bolt carrier)

p pressure in bolt carrier cavity (expansion chamber)

$\overset{*}{p}$ pressure at gas port

p_i atmospheric pressure

p_o pressure in gun tube (reservoir)

p_{o_i} initial pressure in gun tube (reservoir)

q heat conducted through wall of gas tube

s displacement of bolt carrier from initial position

s_i initial displacement of bolt carrier

s_v displacement of bolt carrier at vent location

s_E displacement of bolt carrier at end of expansion chamber

t time

t_i initial time

v velocity of propellant gas

$\overset{*}{v}$ velocity of the gas at gas port

v_i initial velocity of propellant gas

v_p velocity of bolt carrier

v_{p_i} initial velocity of bolt carrier

A cross-sectional area of bolt carrier cavity (expansion chamber)

$\overset{*}{A}$ cross-sectional area of gas tube at gas port

A_v cross-sectional area of vent holes in bolt carrier

C_v specific heat at constant volume of propellant gas

F forces opposing motion of bolt carrier (piston)

M_p mass of bolt carrier

R gas constant for propellant gas [$R = p/\rho T$, obtained from measurements]

Re Reynolds number of flow in gas tube, based on cross-section diameter

T temperature in bolt carrier cavity (expansion chamber)

$\overset{*}{T}$ temperature at gas port

T_i initial temperature in bolt carrier cavity (expansion chamber)

T_o temperature in gun tube (reservoir)

T_{o_i} initial temperature in gun tube (reservoir)

T_w temperature of wall of gas tube

V volume of bolt carrier cavity (expansion chamber)

V_i initial volume of bolt carrier cavity (expansion chamber)

γ effective ratio of specific heats in gas tube

$\bar{\gamma}$ effective ratio of specific heats in gun tube (reservoir)

μ absolute viscosity of gas

ρ density of gas in bolt carrier cavity (expansion chamber)

$\overset{*}{\rho}$ density of gas at gas port

ρ_i initial density of gas in bolt carrier cavity (expansion chamber)

ρ_o density of gas in gun tube (reservoir)

The equations are as follows:

Let $e = C_v T$,

$$\frac{dq}{dt} = (0.14020)\, Re^{-1/4}\, \frac{k}{\mu}\, (\overset{*}{T} - T_w)\, \ell \overset{*}{A}{}^{1/2}\, \overset{**}{\rho v}$$

$$V = V_i + As$$

$$\varepsilon = 1 \text{ for } t \leq t\,(s_E)$$

$$\varepsilon = 0 \text{ for } \geq t\,(s_E)$$

$$K_1 = \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/\,[2(\gamma-1)]} \quad \text{for } s \geq s_v; \quad K_1 = 0 \text{ for } s \leq s_v$$

$$K_2 = \left(\frac{2}{\gamma+1}\right)^{(3\gamma-1)/[2(\gamma-1)]} \quad \text{for } s \geq s_v; \quad K_2 = 0 \text{ for } s \leq s_v$$

$$p = R\rho T$$

Then the differential equations for v_p, s, ρ, T as functions of t are:

$$\frac{dv_p}{dt} = \varepsilon \left[\frac{R\rho TA}{M_p} + \frac{1}{M_p} F\right] \quad F = 0 \text{ in absence of friction.}$$

$$\frac{ds}{dt} = \varepsilon v_p$$

$$\frac{d\rho}{dt} = \frac{\overset{***}{\rho A v} - \rho A v_p - K_1 A v (\gamma \rho p)^{1/2}}{V}$$

$$\frac{dT}{dt} = \left(\frac{1}{C_v \rho V}\right) \left[\overset{***}{\rho A v}\left(\frac{\overset{*}{p}}{\overset{*}{\rho}} + \overset{*}{e} + \frac{\overset{*}{v}{}^2}{2} - \frac{dq}{dt} - V\left(e + \frac{v_p^2}{2}\right) \frac{d\rho}{dt}\right.\right.$$

$$- \rho V v_p \frac{dv_p}{dt} - \rho A v_p \; \frac{p}{\rho} + e + \frac{v_p^2}{2} - K_1 A_v e\, (\gamma p \rho)^{1/2}$$

$$\left. - (\gamma+1)\, K_2 A_v p (\gamma p/\rho)^{1/2}\right]$$

NOTE: At $s = s_E$, v_p becomes zero and remains zero.

Initial conditions:

$$t_i = 0 \quad ; \quad s_i = 0, \quad v_{p_i} = 0, \quad T_i = T_{o_i}$$

$$p_i = \text{atmospheric pressure} \qquad \rho_i = p_i/(RT_i)$$

Preliminary calculations:

Given: $p_o(t)$ in tabular or graphical form, T_{o_i}, $\bar{\gamma}$.

$$T_o(t) = T_{o_i} \, (p_o/p_{o_i})^{[\bar{\gamma} - 1]/\bar{\gamma}} \quad , \quad \rho_o(t) = p_o/(RT_o)$$

$$\overset{*}{p}(t) = \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma - 1)} p_o(t) \quad ; \quad \overset{*}{T}(t) = \left(\frac{2}{\gamma + 1}\right) T_o(t)$$

$$\overset{*}{\rho}(t) = \left(\frac{2}{\gamma + 1}\right)^{1/(\gamma - 1)} \rho_o(t); \quad \overset{*}{v}(t) = \left[\frac{2\gamma}{\gamma + 1} \frac{p_o}{\rho_o}\right]^{1/2}$$

These equations have been programmed for the digital computer. The input required is pressure at the gas port versus time, weapon parameters, and initial conditions.

III. EXPERIMENTATION

A. Test Plan

The basic test plan was to obtain three complete sets of data for each value of a parameter. From each group of three, one typical set of data was selected for complete analysis and comparison with theory. Lot LC 12304, with ball projectile and ball propellant, was used throughout the experiment. Magazines were loaded with one dummy and one live round so that the dummy round was chambered after firing the live round.

Parameters were varied as follows:

Initial Temperature of Gas Tube

80°F = 300°K (Nominal)

205°F = 370°K

332°F = 440°K

584°F = 580°K

Diameter of Gas Port

0.032 inch

0.060 inch

0.092 inch (Nominal)

0.094 inch

0.120 inch

Diameter of Gas Tube within Key

0.1795 inch (Nominal)

0.1777 inch

0.1728 inch

Diameter of Vent Holes in Carrier

0.109 inch (Nominal)

0.000 inch

B. Procedures and Instrumentation

1. Rifle and Mount. A modified M16A1 Rifle was supported by six wires comprising a frictionless mount. The wires were attached to lightweight crossarms which in turn were attached to the rifle. The assembly was balanced so that the center of gravity of the assembly was located on the centerline of the bore. To control the motion of the rifle, a calibrated set of springs was mounted between the rifle and a relatively rigid backstop. The centerline of the spring system was aligned with the centerline of the bore as shown in Figure 2.

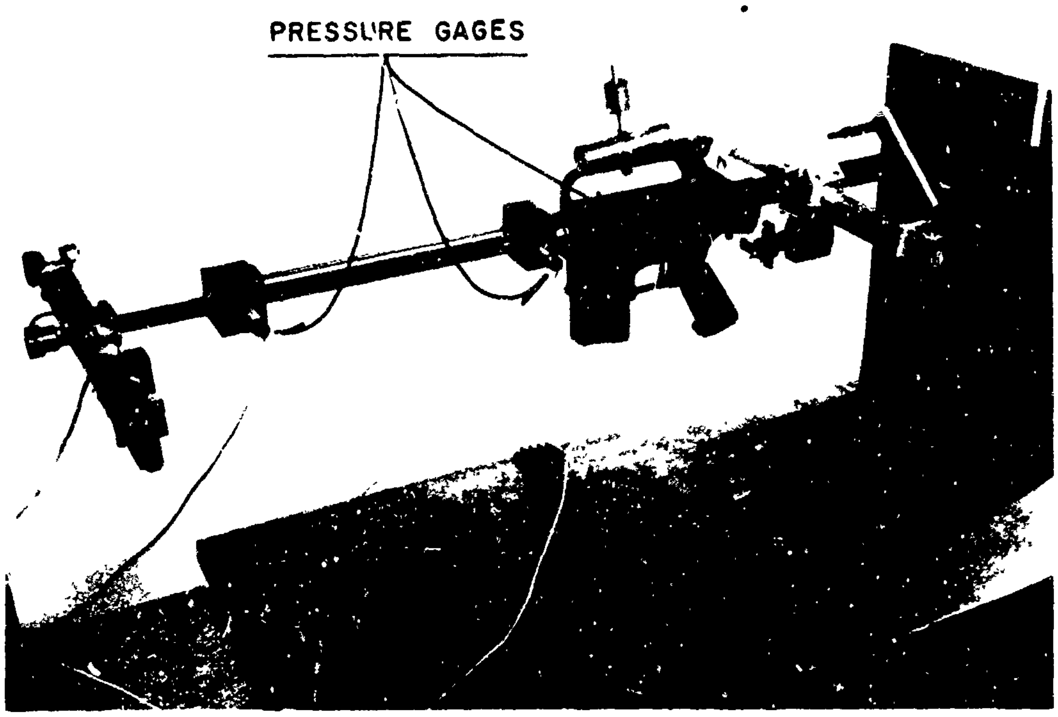

Figure 2. Rifle Mount

The weapon was fired with a solenoid attached to the rear cross-member as can be seen in Figure 2. The solenoid was controlled by a sequence timer as were recording devices and camera shutters.

A photocell[2] was used to provide a signal when the base of the projectile emerged from the muzzle. The photocell was mounted in a radial hole in an adapter attached to the muzzle.

2. Displacement versus Time Measurements. Displacement versus time of reflectors placed on the left side of the bolt carrier and receiver were recorded on photographic paper with a drum camera.[3] Timing lines were produced on the record by a stroboscopic light within the camera. The time of base emergence was indicated on the record by a flash tube within the camera. The flash tube was triggered by the pulse circuit initiated by the photocell at the muzzle.

3. Pressure versus Time Measurements. Pressure versus time[4] was measured at the mouth of the cartridge case, at the gas port, and in the bolt carrier cavity. "Mini Hat" pressure gages[5] were placed in gage adapters at the mouth of the cartridge case and at the gas port. A Kistler Type 601H was threaded into an adapter through the side of the bolt carrier. The signals from the pressure gages were recorded on a 14-channel magnetic tape recorder along with a time reference and the pulse from the photocell circuit. The gage installations are shown in Figures 2 and 3.

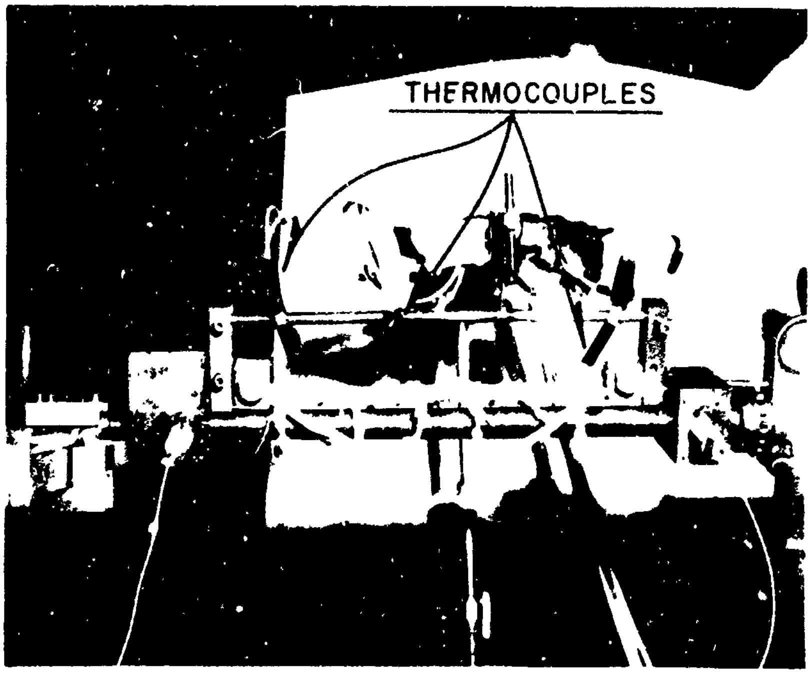

Figure 3. Installation of Pressure Gages and Thermocouples

4. Temperature Measurements. The ambient temperature was measured with a thermometer, and the rise in temperature in the gas tube from preheating and from firing was measured with thermocouples.

Chromel-alumel thermocouples were spot welded to the gas tube at three locations as shown in Figure 3. Initial temperatures were elevated by passing current through the gas tube. The signals from the thermocouples were also recorded on the magnetic tape recorder.

5. Velocity Measurements. Velocities of the projectiles were calculated from measurements of the transit times and distance between lumiline screens located down range. The transit times were read directly on electronic counters that were started and stopped by the lumiline screens.

C. Data Reduction

1. Displacement versus Time. The photographic displacement versus time records were digitized using a Universal Telereader connected to a card punch. The BRLESC digital computer calculated displacement and velocity of the bolt carrier and receiver relative to the mount and prepared the displacement data for automatic plotting. An example of the results is presented in Figure 4.

The points where venting and extraction begin are indicated on the carrier trace. The point where extraction begins is also the point where expansion of the cavity in the carrier ceases. Zero on the time axis indicates the time of shot ejection.

2. Pressure versus Time. The magnetic tape records of pressure were digitized by an Astrodata analog to digital converter. The BRLESC computer converted the data to pressure versus time, calculated integrals, and prepared the results for automatic plotting. Examples of the plots are presented in Figures 5, 6, 7, and 8. Zero on the time axis indicates the time of shot ejection.

3. Miscellaneous. Temperature versus time and projectile velocities were calculated by hand.

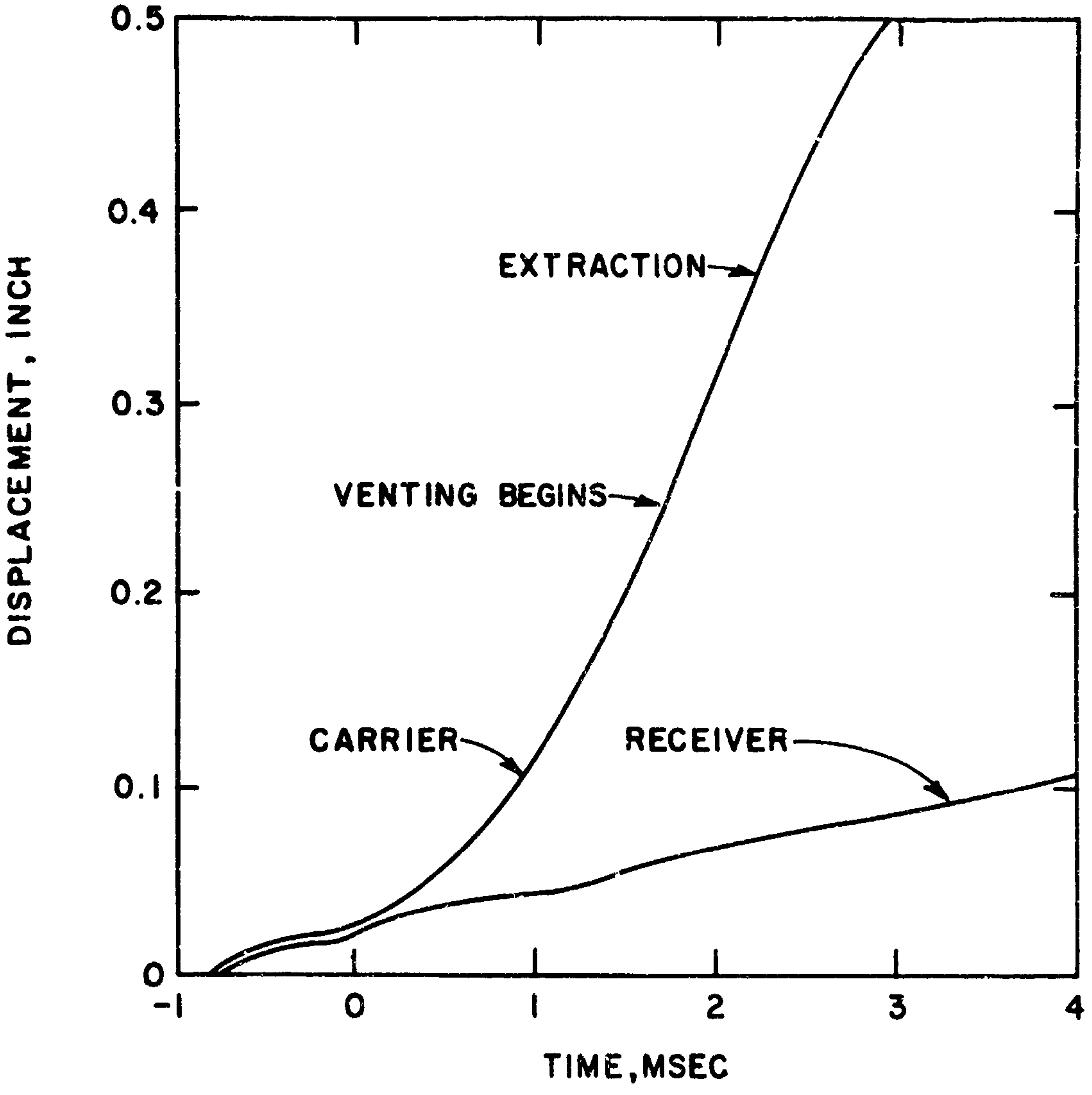

Figure 4 - Displacement versus Time of Bolt Carrier and Receiver

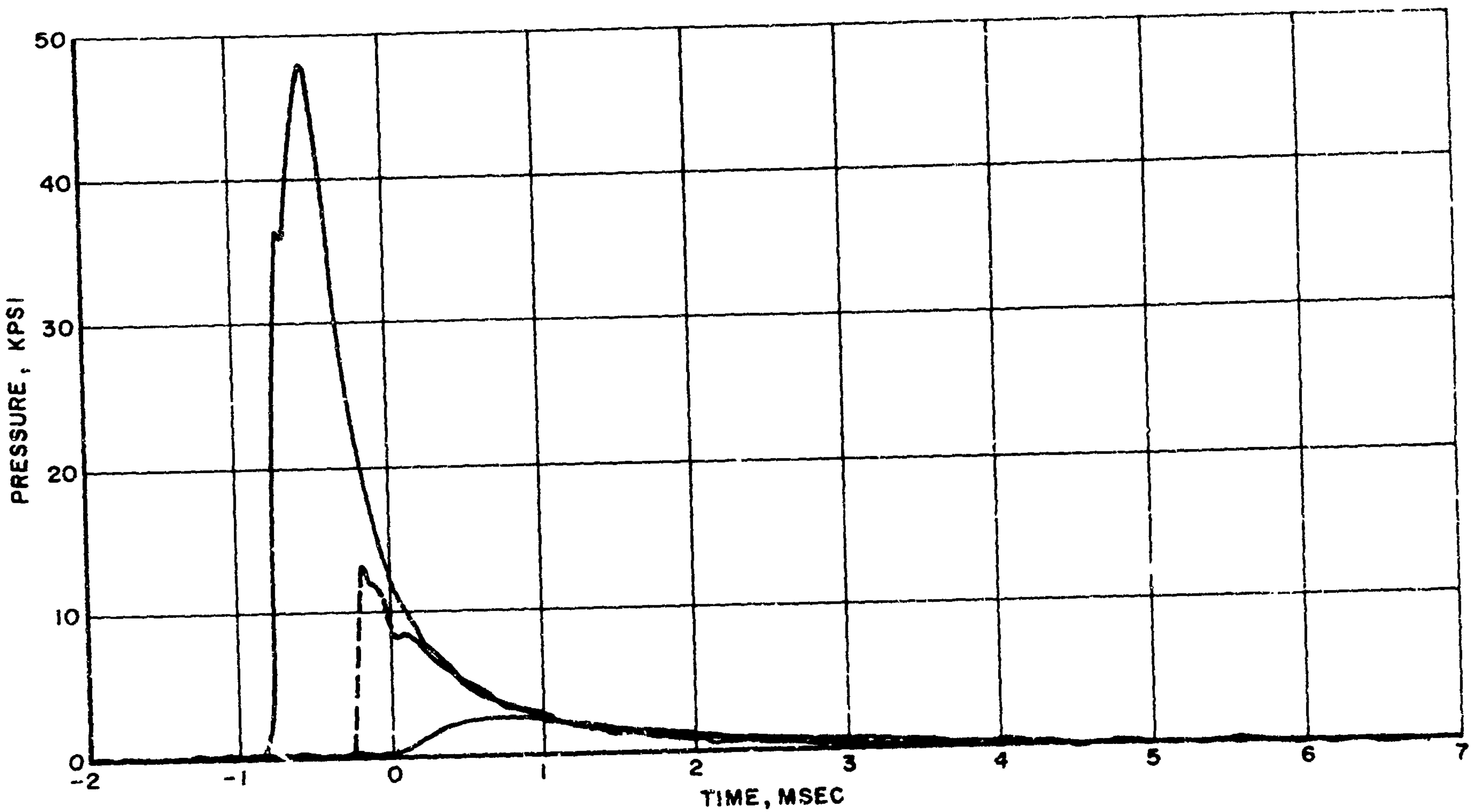

Figure 5 - Combined Pressure Versus Time Curves

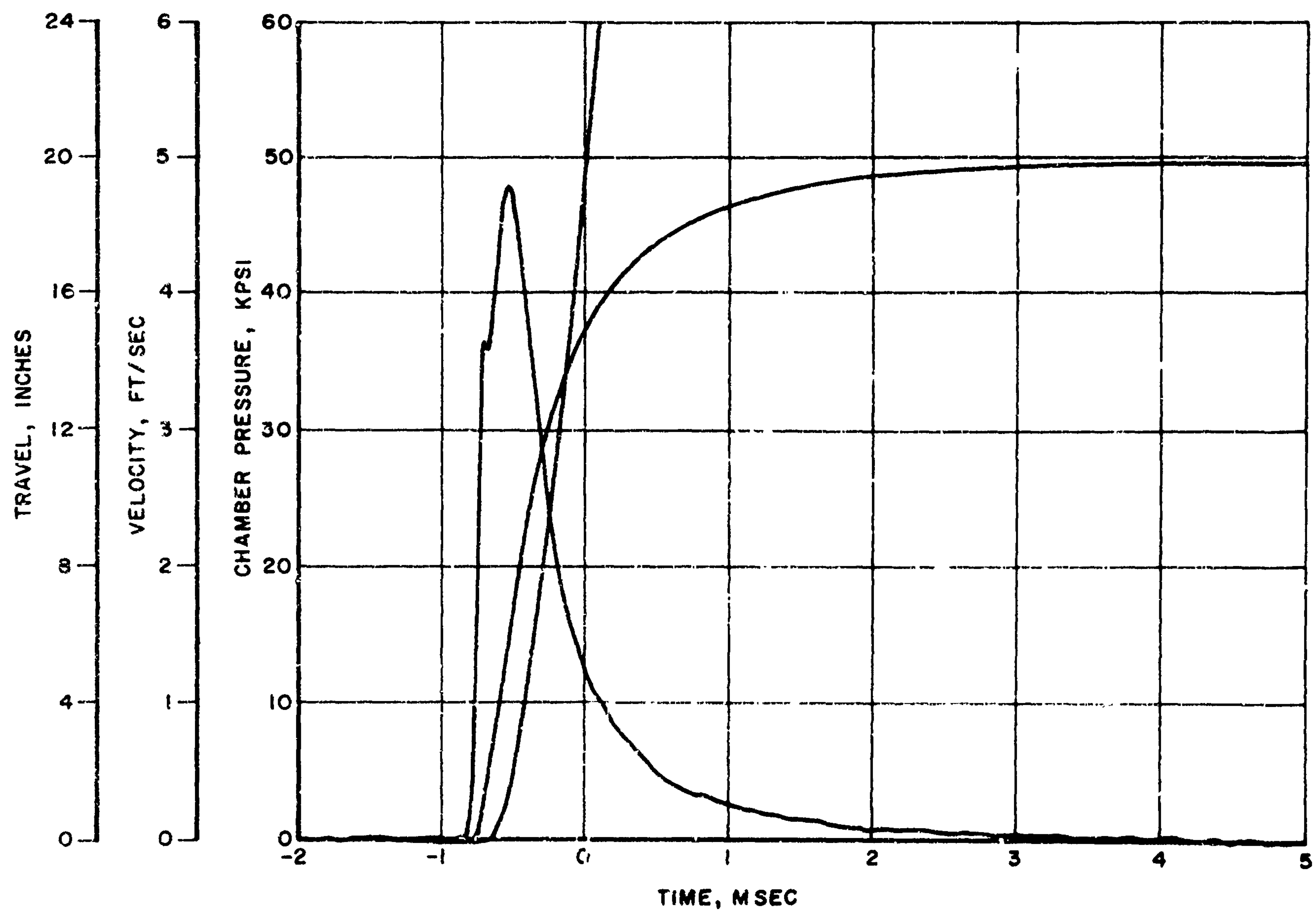

Figure 6 - Pressure Versus Time at Mouth of Cartridge Case With Integrals

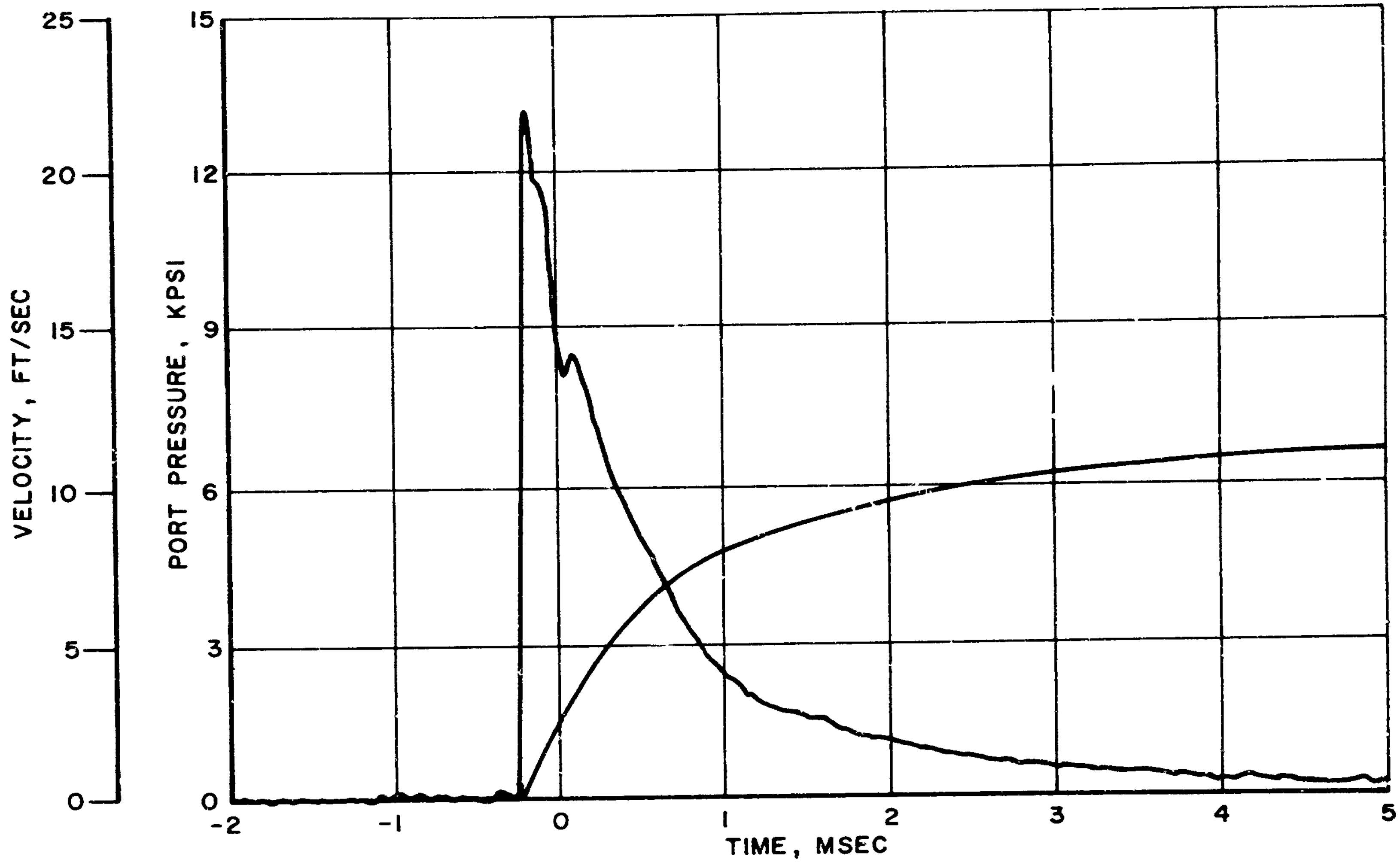

Figure 7- Pressure Versus Time at Gas Port With Integral

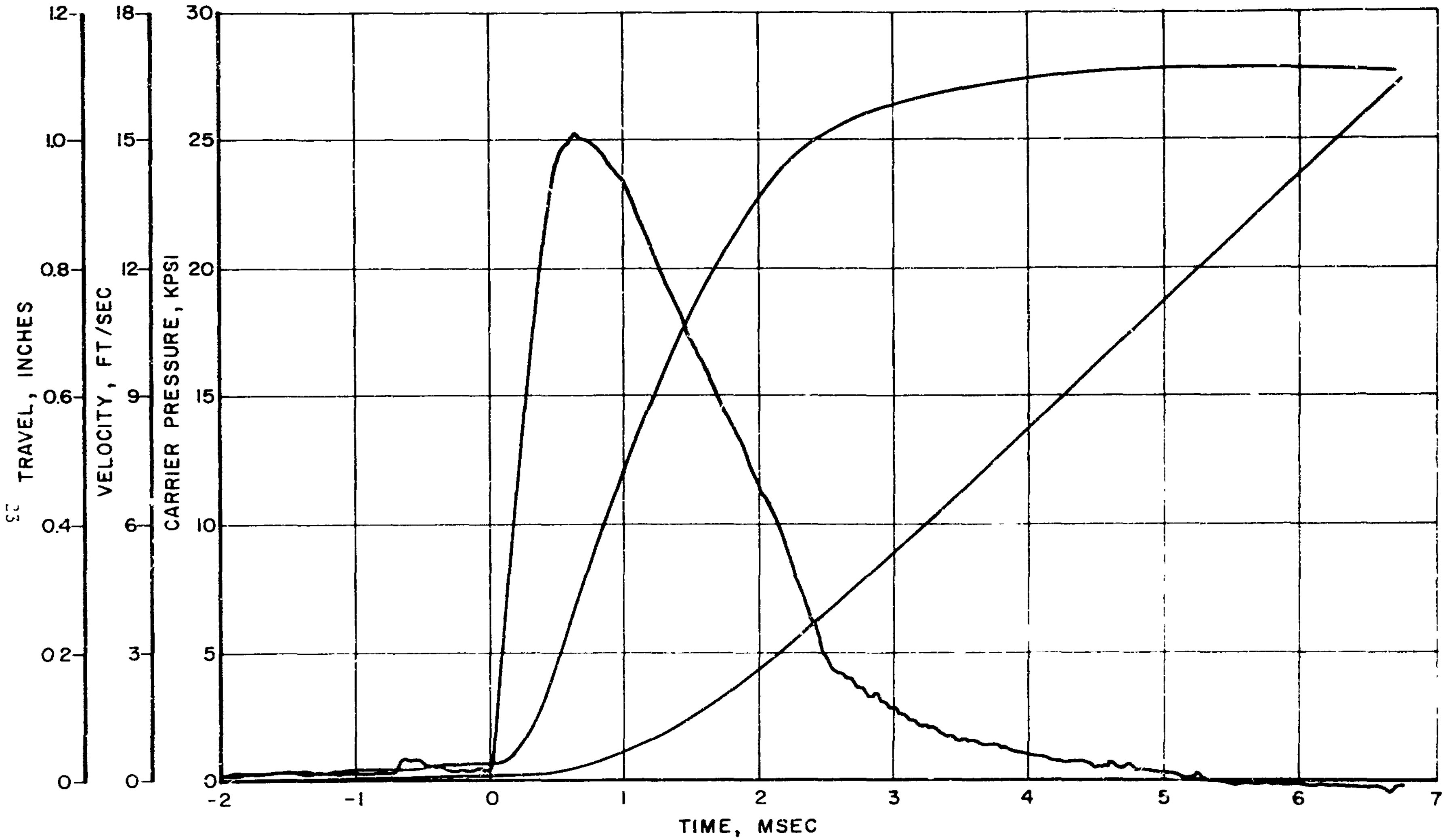

Figure 8 - Pressure Versus Time at Carrier Cavity With Integrals

IV. COMPARISON OF THEORY AND TEST RESULTS

A. Approach

Two approaches were taken in using the equations to calculate carrier cavity pressure. The first consisted of repeatedly running the program with the same port pressure history where, for each run, a single weapon parameter was changed. Most of the parameters in the equations were varied beyond the practical range. The second approach was to use the measured port pressure history for a particular round along with the values of the weapon parameters for that round.

The results are plotted in two ways. First, in the case where tests were performed, the measured cavity pressure is plotted with the cavity pressure calculated from the measured port pressure. Second, ratios of measured and calculated quantities are plotted versus the ratio of the varied parameter to its nominal value. Nominal refers to the values indicated in the "Test Plan" section. The following ratios are considered.

1. Ratio of maximum carrier velocity measured or calculated with varied parameters to maximum carrier velocity determined with nominal values of the parameters.

2. Ratio of the integral of the cavity pressure to the integral of the port pressure, both integrated up to the time of extraction t_E.

3. Ratio of the peak cavity pressure to the peak port pressure.

The following plotting symbols are used.

. Results from theoretical calculations based on a single record of port pressure versus time.

⊕ Results from theoretical calculations based on the port pressure measured during experiments in which parameters were varied.

⊡ Results from measurements made during experiments in which parameters were varied.

B. Summary of Test Data

The table on the following page indicates the consistency of the ammunition and gages used and shows briefly the effect on functioning caused by the changes in parameters.

C. Effect of Varying the Initial Temperature of the Gas Tube

The measured and calculated pressure in the cavity are plotted in Figure 9. The measured curves have no significant differences arising from changing the initial temperature.

Ratios of measured and calculated quantities are plotted versus the ratio of initial to nominal temperature in Figure 10. The ratios were calculated from the temperatures expressed in degrees Kelvin. The effects arising from varying the initial temperature are rather small.

D. Effect of Varying Port Diameter

The port diameters used in the test were 0.030, 0.060, 0.092, 0.094, and 0.120 inch. The effect on the functioning of the weapon indicates that the practical limits for the port diameter lie between 0.060 and 0.120 inch, assuming no other parameter is changed. With the smaller port the bolt-carrier buffer failed to reach the rear of the receiver and with the larger port the buffer button was compressed to the extent the carrier key impacted the rear of the receiver.

The theoretical and measured pressure curves are plotted in Figure 11. The theory over predicts for the larger than normal gas ports and under predicts for the smaller.

Ratios of measured and calculated quantities are plotted versus the ratio of varied to nominal port area in Figure 12. These curves show a strong dependence on the gas port area.

SUMMARY OF TEST DATA

Round Ident.	Condition	Cycle Time msec	Muzzle Velocity	Maximum Pressure, KPSI Chamber	Port	Cavity	1st Int Pressure, PSI-SEC Chamber	Port	Cavity
52	Nominal	78	3162	46.2	13.3	2.62	23.3	10.6	4.26
69	Nominal	80	3202	51.6	13.2	2.49	24.8	9.8	4.29
	TEMP. OF GAS TUBE								
109	370°K	78	3212	50.6	13.2	2.53	24.7	9.7	4.22
111	440°K	79	3180	51.2	13.8	2.54	24.3	11.0	4.33
108	580°K	78	3192	50.8	13.3	2.55	25.0	10.4	4.26
	DIAMETER OF GAS PORT								
87	0.032 in.	--	3154	50.7	15.0	0.36	22.6	--	--
94	0.060 in.	91	3125	49.4	13.8	1.76	25.9	12.8	3.90
99	0.094 in.	73	3133	50.0	14.1	2.81	25.3	12.2	4.42
79	0.120 in.	60	3166	52.0	12.8	3.98	25.8	9.8	5.25
	LEAKAGE AREA (GAS PORT 0.094 in.)								
103	0.00099 in.^{2}	76	3165	51.2	13.5	2.70	25.0	10.7	4.11
106	0.00150 in.^{2}	76	3093	50.0	12.8	2.60	27.1	10.6	4.07
107	0.00284 in.^{2}	81	3130	49.8	13.4	2.46	26.1	10.6	3.94
	AREA OF VENTS (GAS PORT = 0.094 in.)								
118	0	73	3160	52.6	13.4	2.69	26.5	10.8	4.46
		AVERAGE	3160	50.5	13.5		25.1	10.8	
		STD. DEV.	33	1.6	0.6			0.9	

NOTE: 1 - Integrated up to time of shot ejection
2 - Integrated up to time of extraction

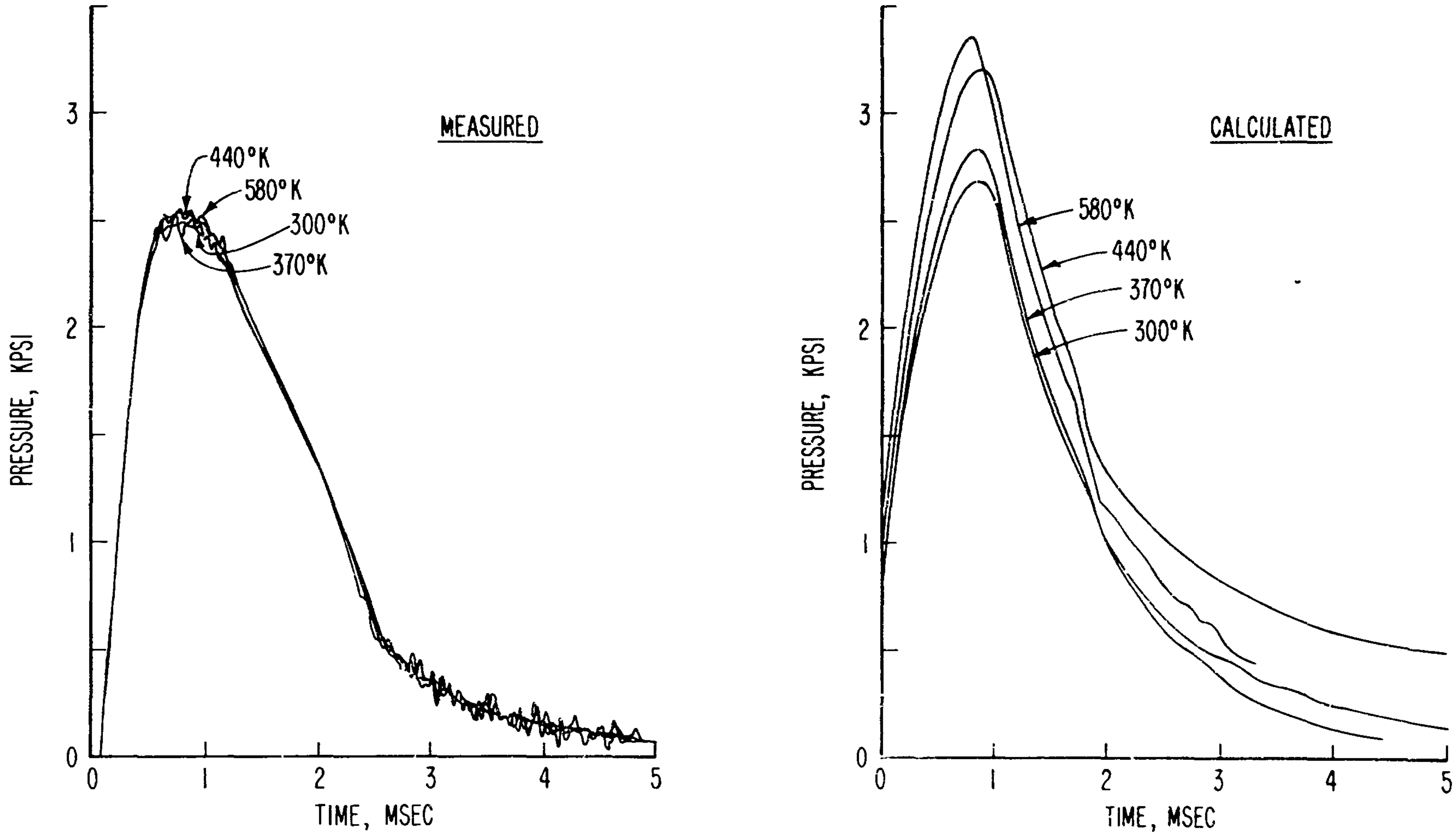

Figure 9 - Effect of Initial Temperature of Gas Tube on Pressure in the Cavity

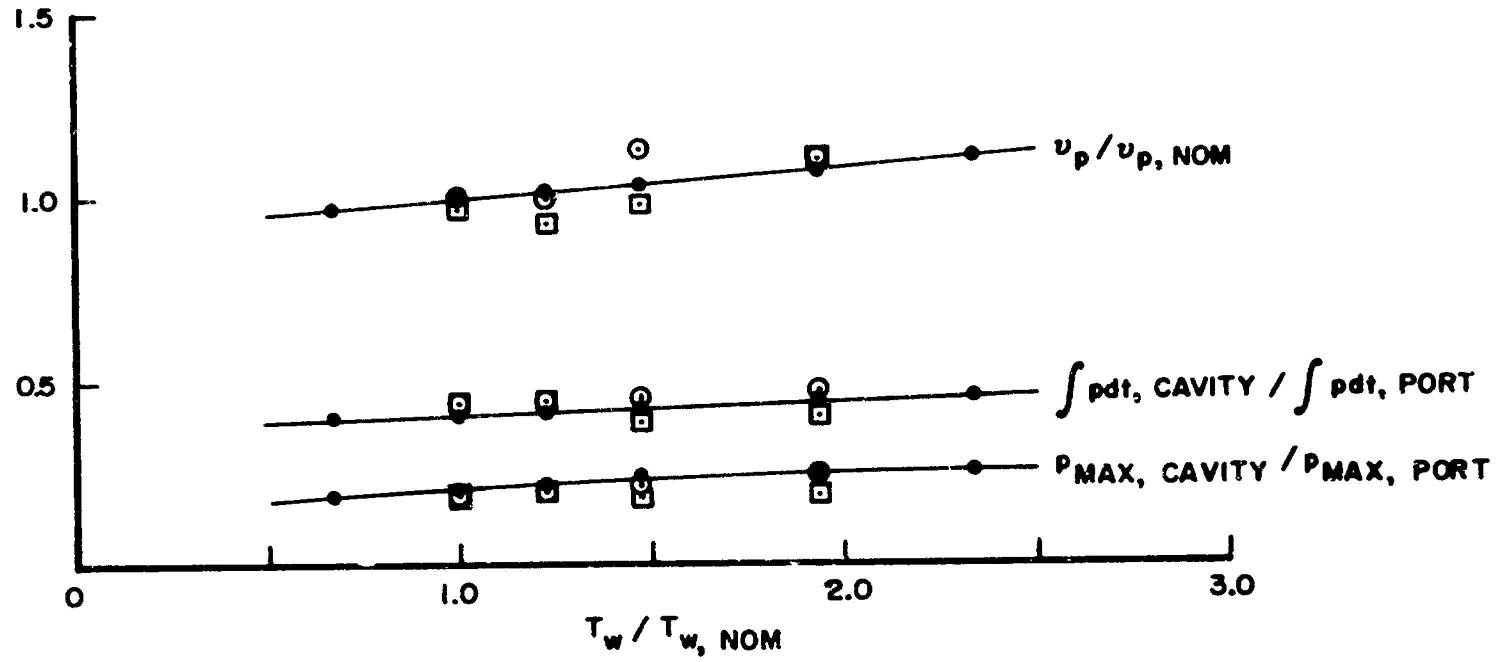

Figure 10 - Effects of Varying Initial Temperature

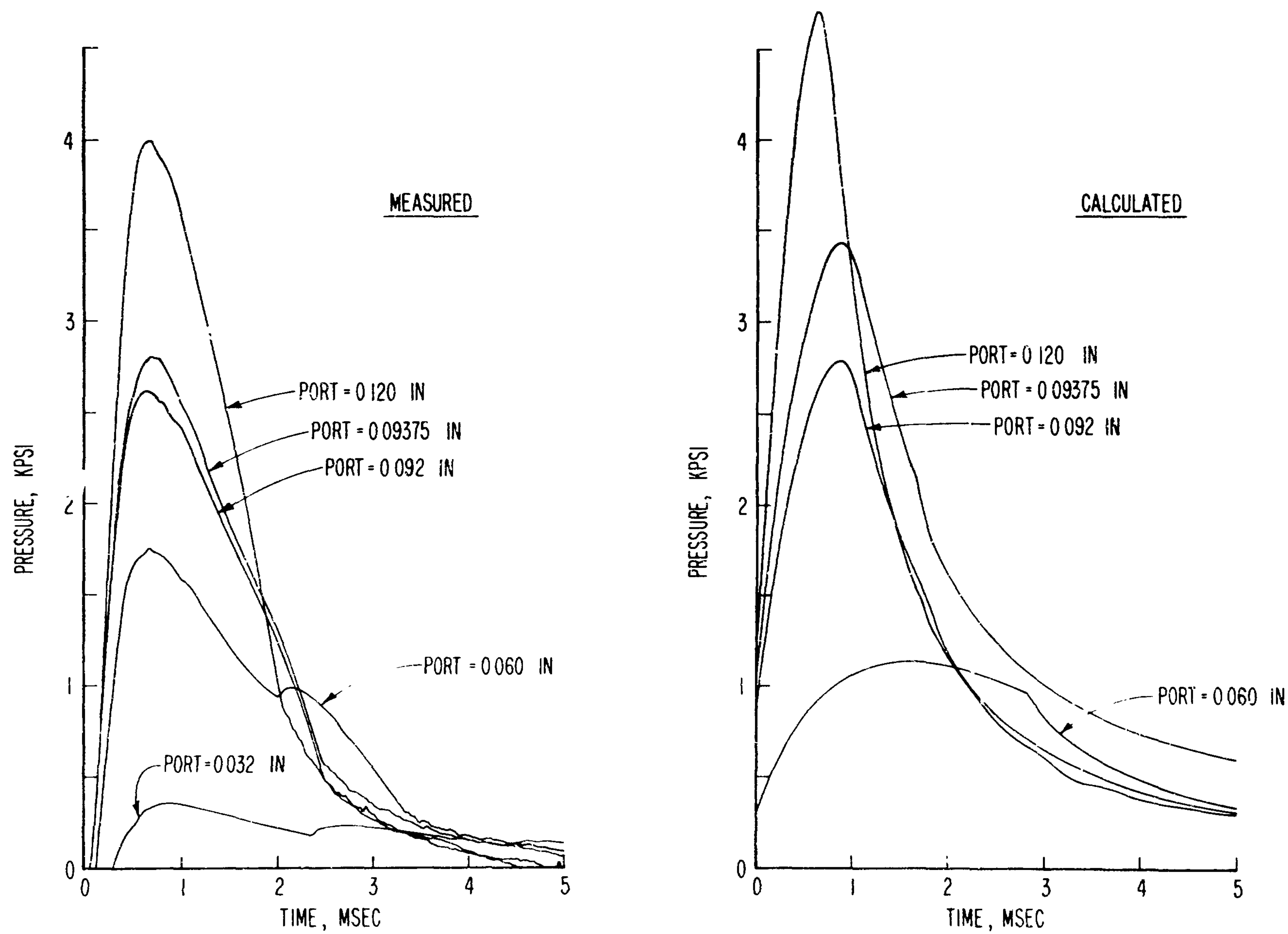

Figure 11 - Effect of Gas Port Area on Pressure in the Cavity

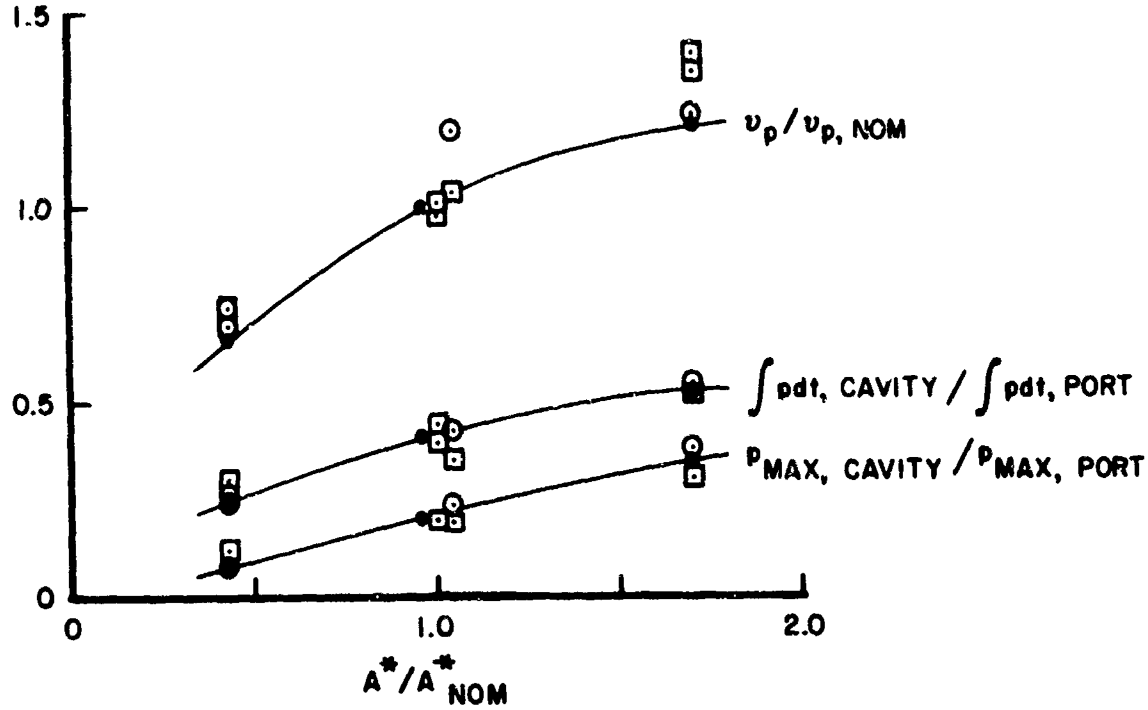

Figure 12 - Effects of Varying Gas Port Area

E. Effect of Varying Leakage Area

Leakage in the gas system takes place, for the most part, around the gas tube in the carrier key and around the rear of the bolt in the carrier. The combined leakage area of the instrumented gun used in this study was 0.00108 in.^{2}, except for this particular test. A tube was chosen that provided a leakage area of 0.00099 in.^{2} and, by reducing the outside diameter, provided 0.00150 in.^{2} and 0.00284 in.^{2}. The areas used for the calculations ranged from zero to 0.002845 in.^{2}.

The theoretical and measured pressure curves are plotted in Figure 13. Larger leakage areas result in lower cavity pressures.

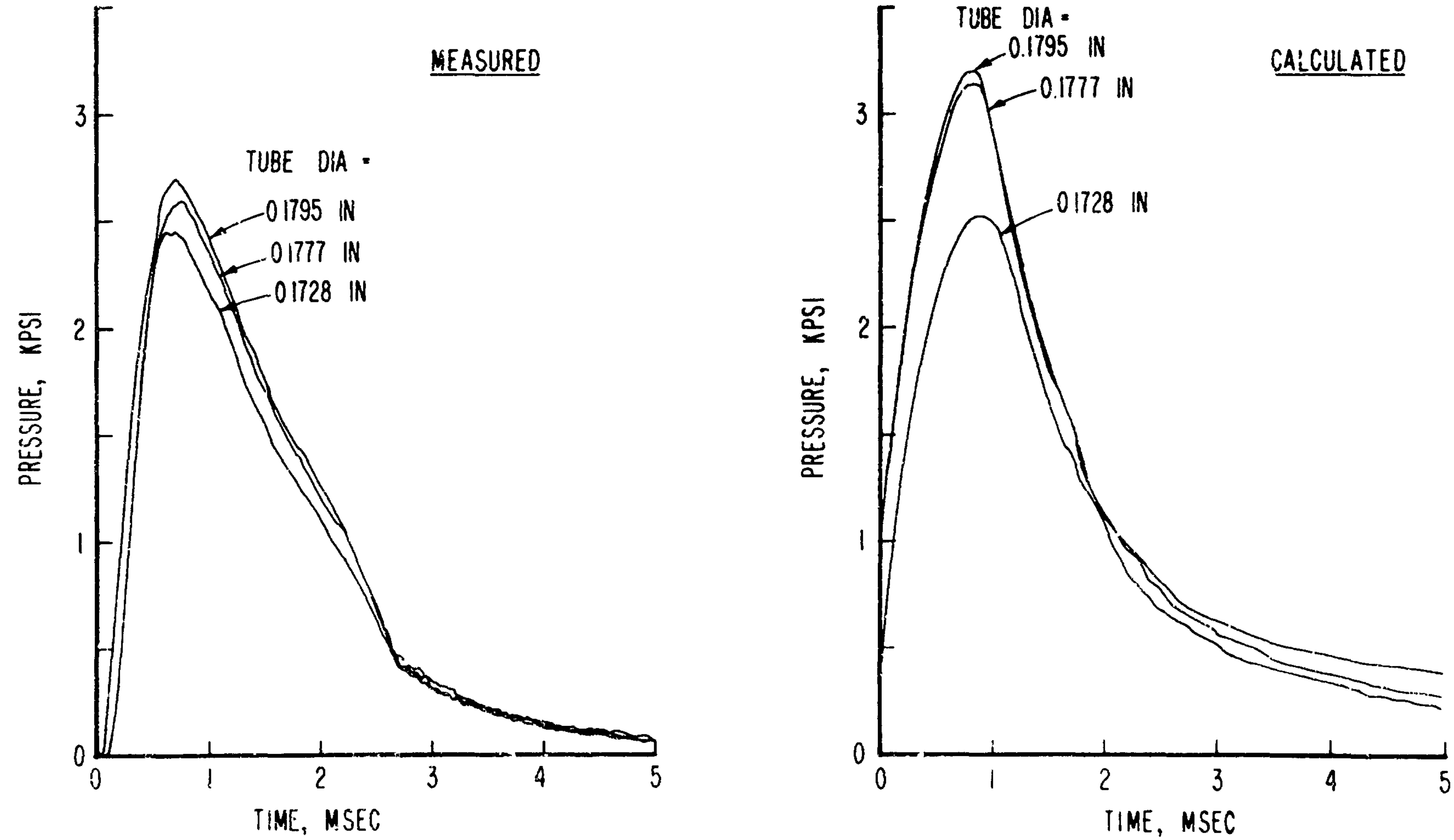

Figure 13-Effect of Leakage Area on Pressure in the Cavity

Ratios of measured and calculated quantities are plotted versus the ratio of varied leakage area to the nominal leakage area in Figure 14. The curves indicate that variations in leakage area within the range investigated have little effect on weapon functioning.

F. Effect of Varying Vent Area

Two vent areas were used in the test; nominal and zero. The nominal area of the vent holes is 0.01866 in.^{2}; however, the flow is always more or less obstructed. Thus, for the calculations, the value for the vent area was taken as half that of the holes.

The theoretical and measured pressures in the cavity are plotted in Figure 15. The effect of venting is seen in the calculated curves although the pressure levels with venting are higher than the pressure levels without venting. The difference in levels arises from differences in the measured port pressure curves used as inputs for the calculations.

Changing the vent area affects only the latter part of the pressure curve. Since venting normally begins after the pressure in the cavity has reached maximum, and since the vent area considered here is small with respect to the pressure area, the effect on acceleration of the carrier is slight.

Ratios of measured and calculated quantities are plotted versus the ratio of varied to nominal vent area in Figure 16. The curves indicate that weapon functioning is independent of the vent area. The vents relieve the pressure in the bolt carrier cavity so that it does not apply force on the cam pin after unlocking and may retard fouling of the gas system.

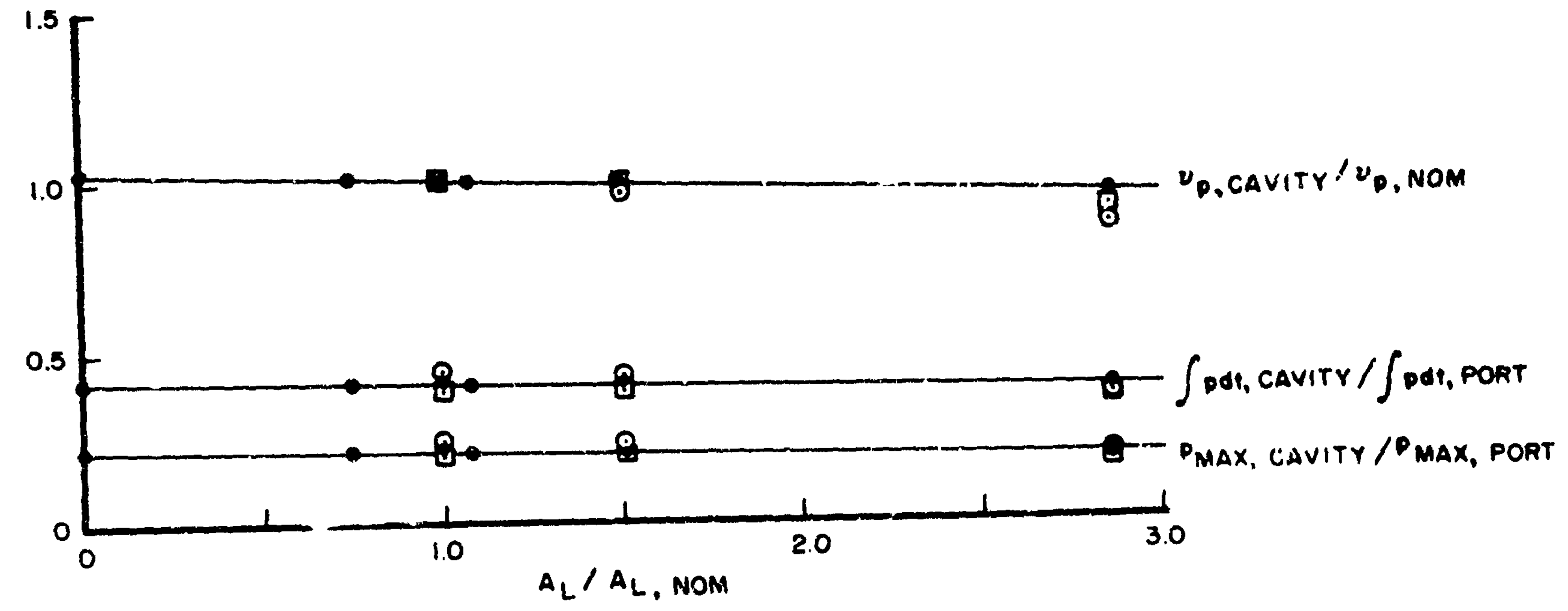

Figure 14 - Effects of Varying Leakage Area

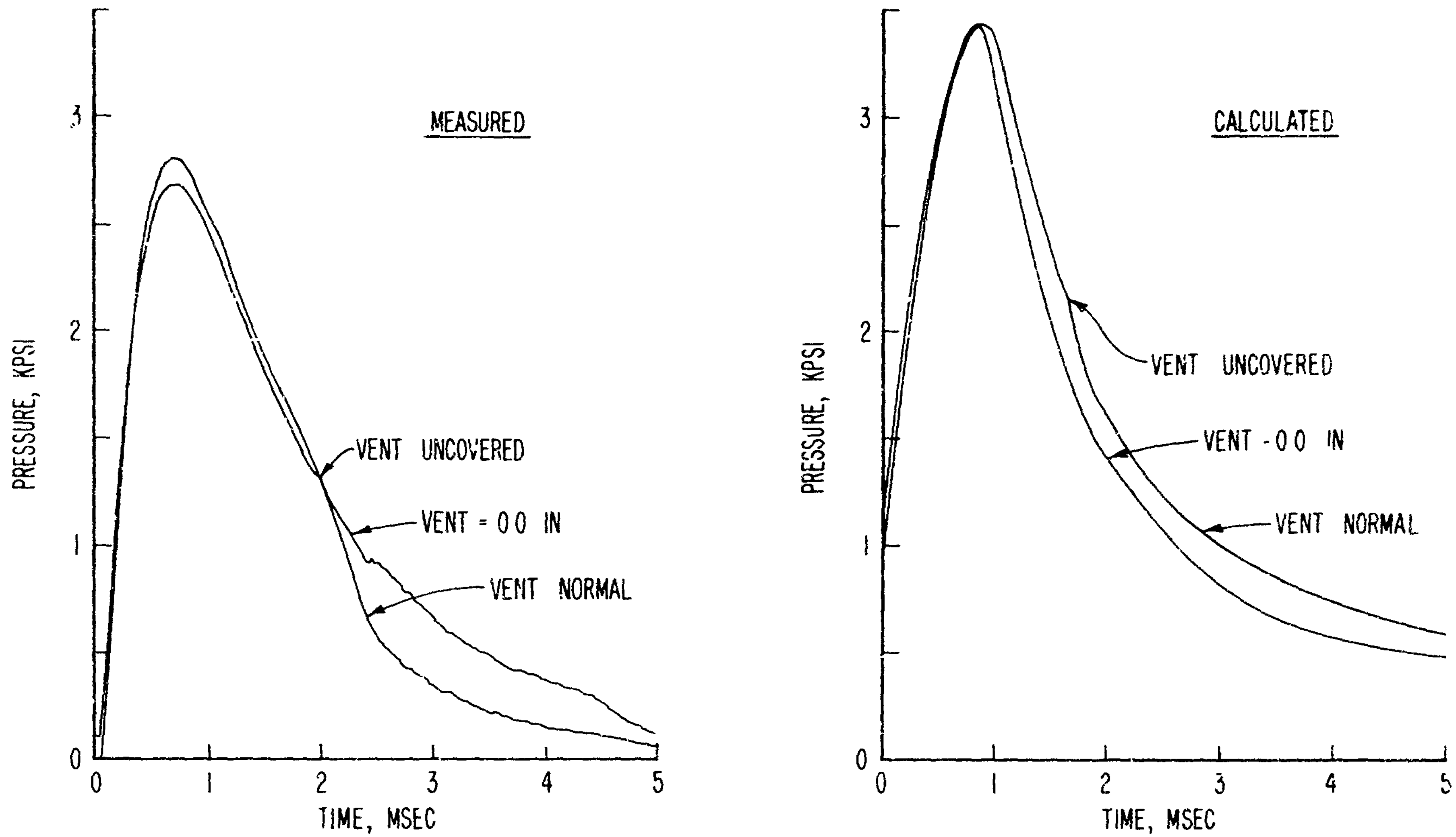

Figure 15 – Effect of Vent Area on Pressure in the Cavity

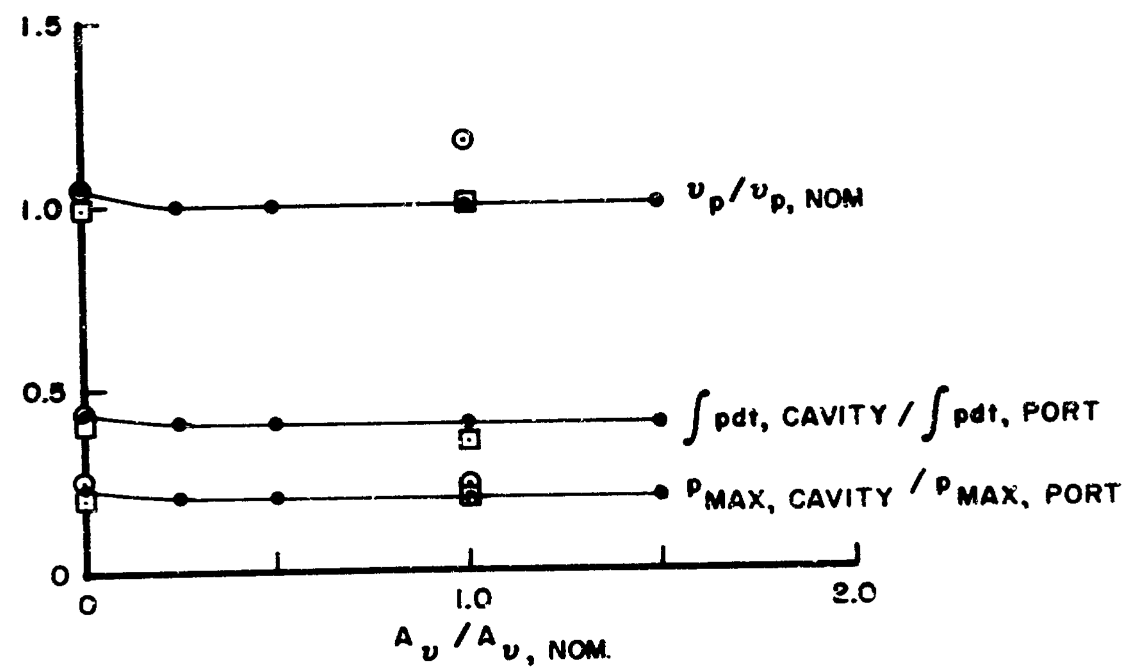

Figure 16 - Effects of Varying Vent Area

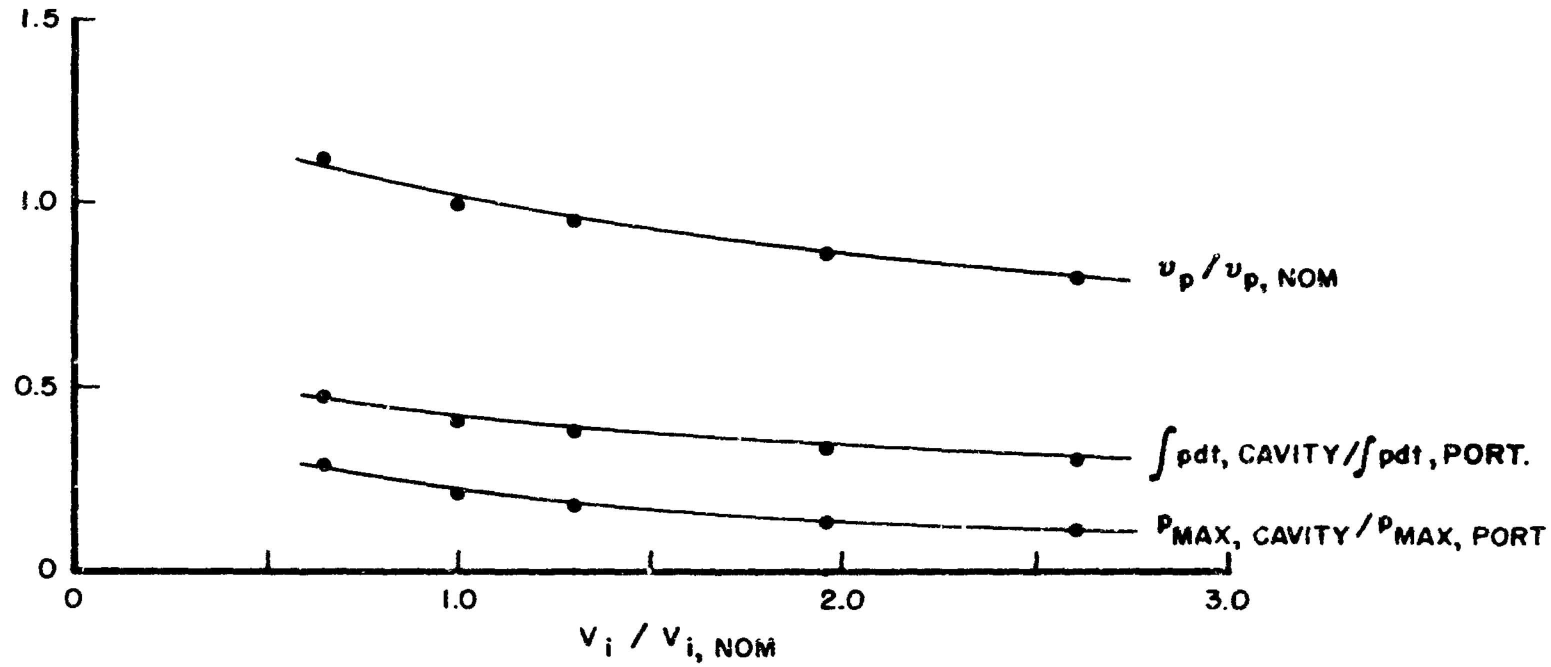

Figure 17 - Effects of Varying Initial Volume

G. Theoretically Determined Effects of Varying Other Parameters

1. Effect of Varying Initial Volume. In this test the initial volume of the gas system was not varied; however, the effect was calculated for initial volumes ranging from 0.122 in.^{3} to 0.488 in.^{3}. The nominal value is 0.187 in.^{3}, and includes all passages from the gas port to and including the carrier cavity.

Ratios of calculated quantities are plotted versus the ratio of varied to nominal initial volume in Figure 17.

2. Effect of Varying Pressure Area. The effect of varying the pressure area used in accelerating the bolt carrier was calculated. The pressure area was varied from 0.093 in.^{2} to 0.341 in.^{2}, where 0.172 in.^{2} is nominal. Ratios of calculated quantities are plotted versus the ratio of varied to nominal pressure area in Figure 18. Varying the pressure area has little effect on the maximum pressure in the cavity but directly affects the velocities attained by the carrier as would be expected.

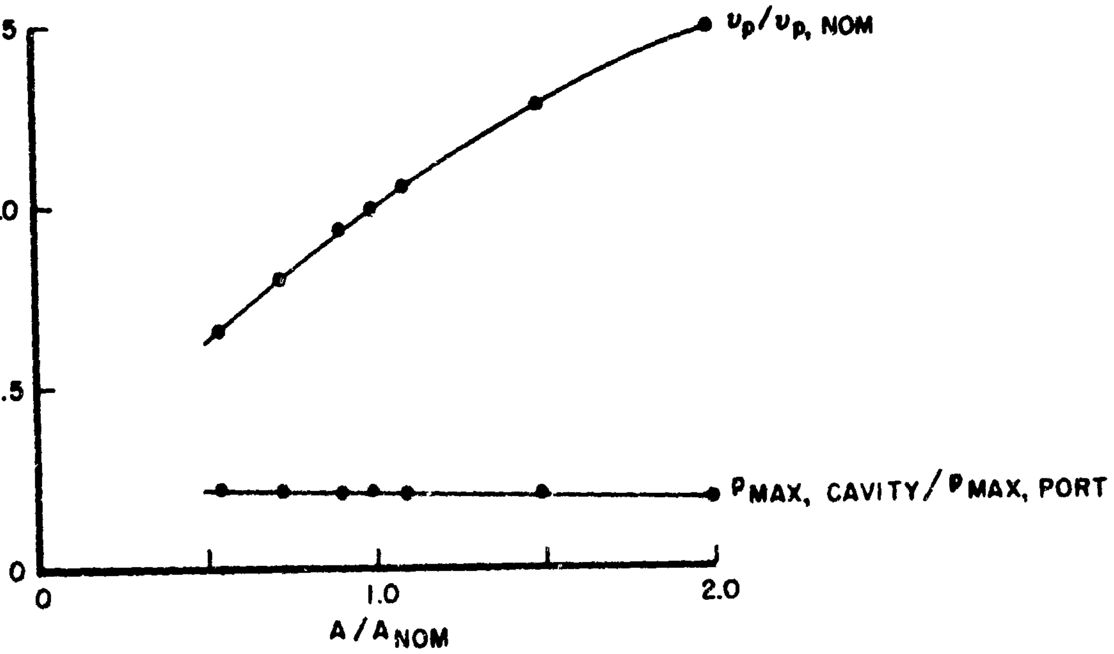

Figure 18 - Effects of Varying Pressure Area

3. Effect of Varying Distance to Vents. The distance the carrier has to move before uncovering the exhaust vents in the cavity was not varied in the test. The effect was calculated. Ratios of calculated quantities are plotted versus the ratio of varied to nominal distance to vents in Figure 19.

As the distance to the vent is decreased the acceleration of the carrier will be decreased. The peak pressure reached in the cavity will be unaffected unless the distance allows opening of the vents before peak pressure is reached.

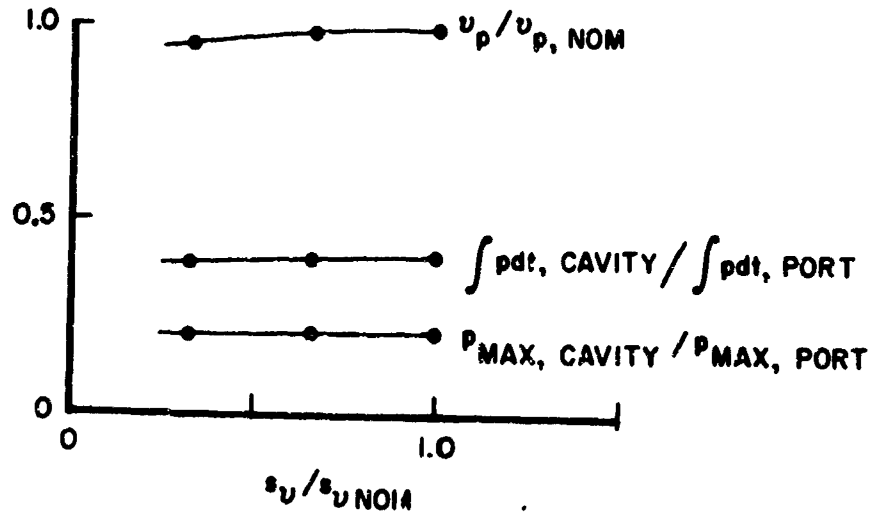

Figure 19 - Effects of Varying Distance to Vents

V. SUMMARY

Agreement between theoretical and experimental results is quite good, indicating the mathematical model of the gas system is adequate.

Results of the study show that functioning of the rifle is quite sensitive to variations in gas port diameter, initial volume, and effective pressure area in the gas system. Further, functioning is quite insensitive to variations in leakage area, vent area, and the distance the bolt carrier travels before uncovering the vent holes in the gas system.

The study has revealed no great advantage in changing any parameter in the M16 gas system. Rather the study shows the role of various parameters and indicates the trade-offs to be expected should changes be proposed.

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